June 10, 2016
Department of Energy, Washington, DC

Project ID # VS136

U.S. Department of Energy Vehicle Technology Office
Annual Merit Review

DOE DE-EE0006444

ePATHS - electrical PCM Assisted Thermal Heating System

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ePATHS Overview

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Timeline

- Start Date – Oct. 1, 2013
- End Date – Dec. 31, 2016
- Percent Complete – 80%

Barriers & Targets

- EV cold weather range +20%
- Phase Change Material (PCM) latent capacity +50%
- Vehicle integrated PCM heating and control system

Budget

- Total project funding: $3.5M
  - DOE share: $1.74M
  - Contractor share: $1.74M
- Funding received in BP-1: $1.1M
- Funding for BP-2: $1.2M
- Funding for BP-3: $1.2M

Note: BP-1 (4Q13 + CY2014 + Jan & Feb 2015)
BP-2 (March – December 2015)
BP-3 (January – December 2016)

Team/Partners

- *Ford Motor Company*
  - Vehicle reqm’ts & controls integration
- *Oak Ridge National Laboratory*
  - Simulation, design & cert. testing
- *Entropy Solutions*
  - High capacity PCM development
- *Project Lead - MAHLE*

Support VTP Efforts by Extending EV Range

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DOE Vehicle Technologies Program (VTP)

- Reduce Petroleum usage and GHG emissions…
- Requires ”…new and more fuel efficient vehicle technologies.”

EV-Everywhere Grand Challenge

- “… produce electric vehicles that are as affordable for the average American family as today’s gas-powered vehicles within the next 10 years (by 2022).”
- Driving range influences consumer acceptance

AOI-11 Advanced Climate Control Auxiliary Load Reduction

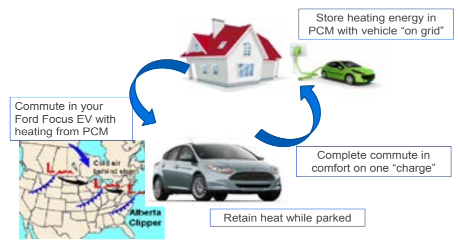
- Advanced HVAC Technologies: increase range
- “…innovative and unique heating…” using phase change materials

Extend GCEV electric range >20% by reducing or eliminating the auxiliary heating load from the vehicle battery at -10°C

- Develop “hot” PCM with >50% increase in latent heat capacity for industry application
- Develop simulation and optimization code for system and components
- Seamless vehicle integration with smart charging and discharging control
- Demonstrate performance and establish commercial viability

FY2016 Objective

- Initial vehicle build and demo on Ford Focus Electric (EV)
- Final vehicle build and demo on Ford Fusion Energi (PHEV)



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Approach/Strategy

General Technical Approach

	Kickoff	Spec, Design	Bench and Mule	Vehicle Integration
		Budget Period I	**Budget Period II**	**Budget Period III**
		17 Months	**10 Months**	**12 Months**
Ford		• *Define System Spec.*	• *Provide car, parts, and consult*	• *Vehicle validation tests*
MAHLE		• *Define Components Spec.* • *Establish system and components design* • *Establish control strategy and spec.*	• *Prototype PCM HX build and test* • *Insulation build* • *Bench and car control dev.* • *Bench build and test*	• *PCM HX Fabrication* • *Vehicle control* • *BEV build and demo* • *PHEV build and demo*
ORNL+MAHLE		• *Components modeling*	• *System modeling* • *Bench validation*	• *Bench validation* • *Car validation*
Entropy+MAHLE		• *PCM development strategy, candidates ident., init. dev.*	• *PCM development*	• *Complete PCM development*

Milestones

Project Execution

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Milestone	Type	Description
System Component Specifications Complete	Technical	The System and component specifications will be complete
Development Level Design Complete	Go/No Go	Development Level designs for the system and components completed and ready for build.

Start 10/1/13 Finish 2/28/15

BP-1 Milestones Accomplished

Milestone	Type	Description
Thermal Energy Storage Demonstration	Go/No Go	Analysis validates that the system approach results in at least 20% increase in electric drive range vs. the baseline vehicle

3/1/15 12/31/15

BP-2 Milestone Accomplished

Milestone	Type	Description
Vehicle Integration System Complete	Technical	Integrated system testing completed and performance targets are achieved
Vehicle Testing Complete	Technical	Vehicle testing complete including evaluation of Thermal Performance, Charging Process, and Range Improvement.

1/1/16 12/31/16

Overall Architecture

ePATHS PCM Thermal Storage System

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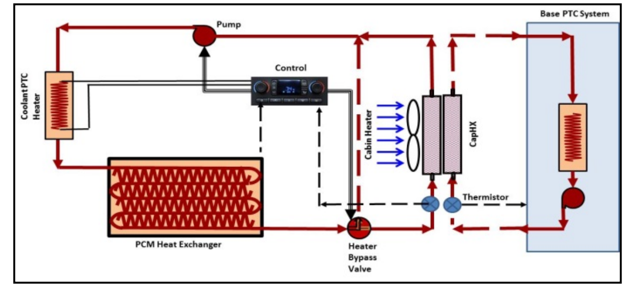
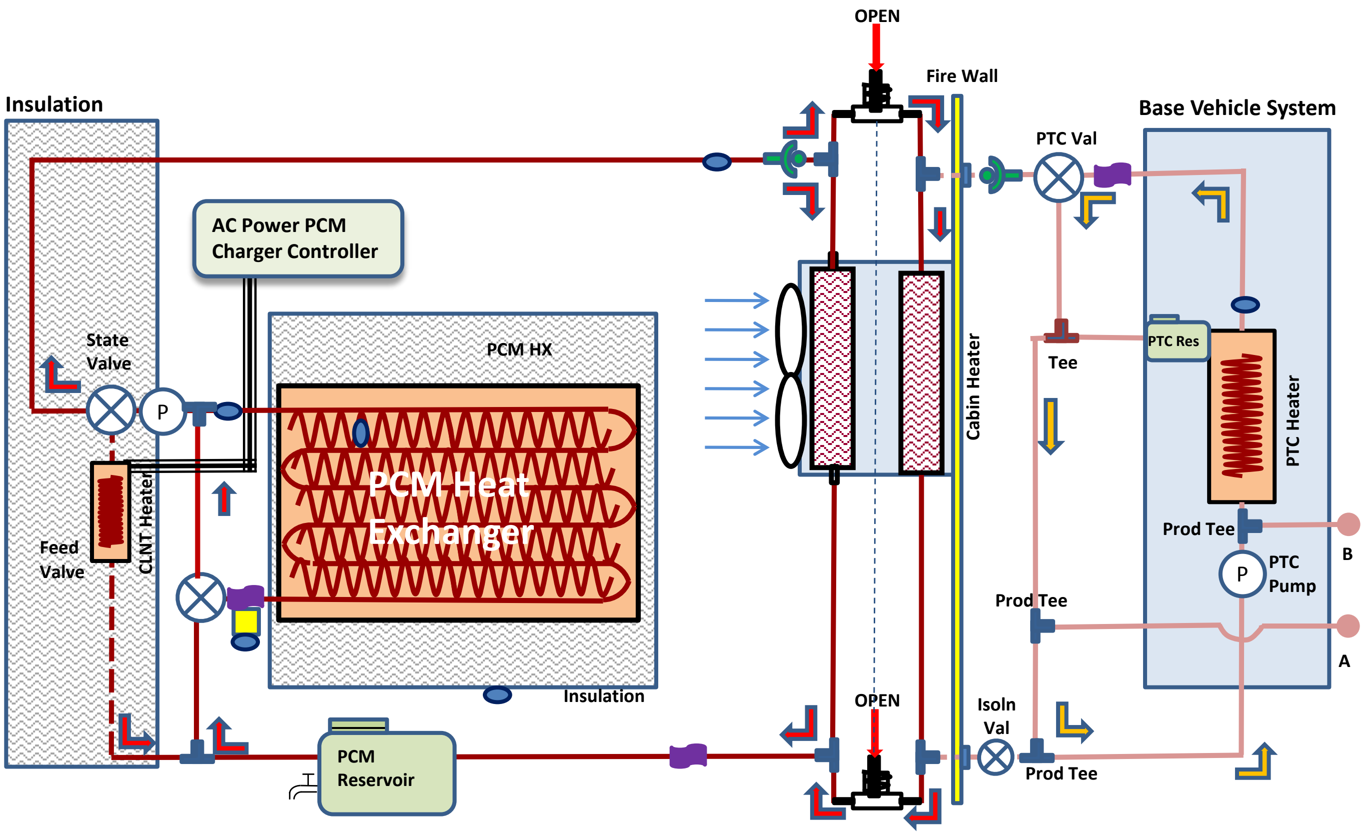


- **System Architecture designed to accommodate 4 modes of operation**



Technical Accomplishments and Progress

PCM Charging

ePATHS PCM Thermal Storage System

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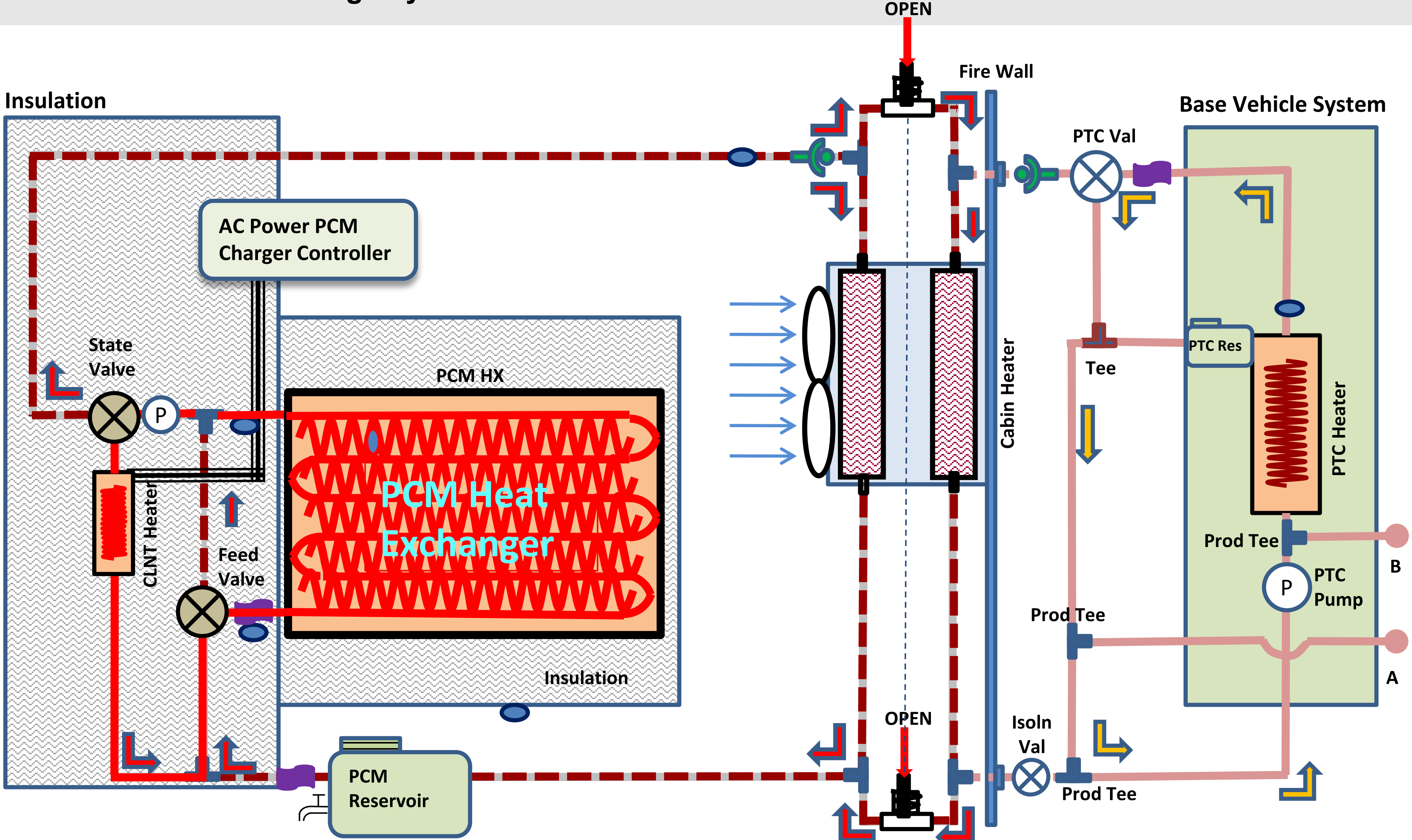

PCM Only Heating

ePATHS PCM Thermal Storage System

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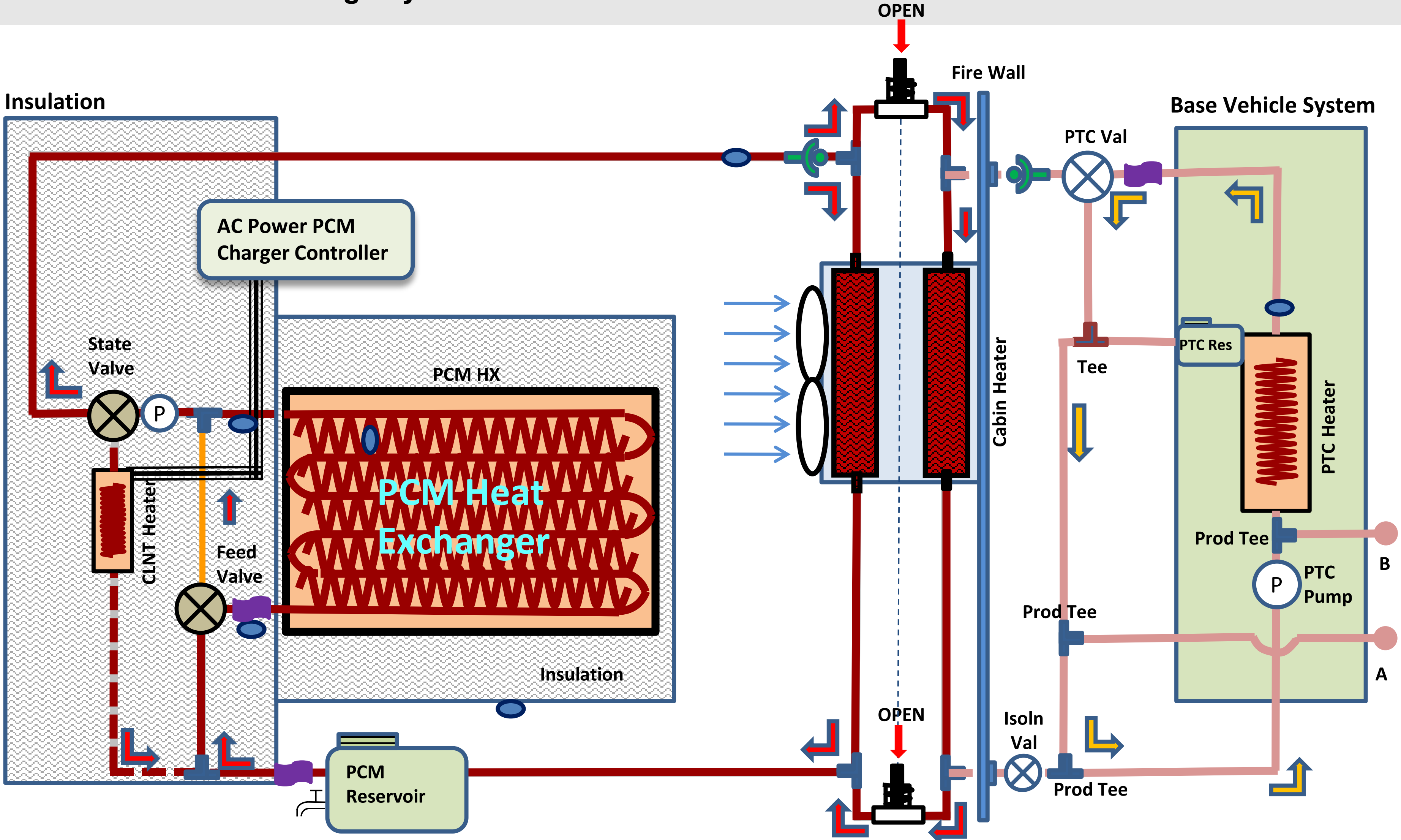

Technical Accomplishments and Progress

PCM Energy Recovery

ePATHS PCM Thermal Storage System

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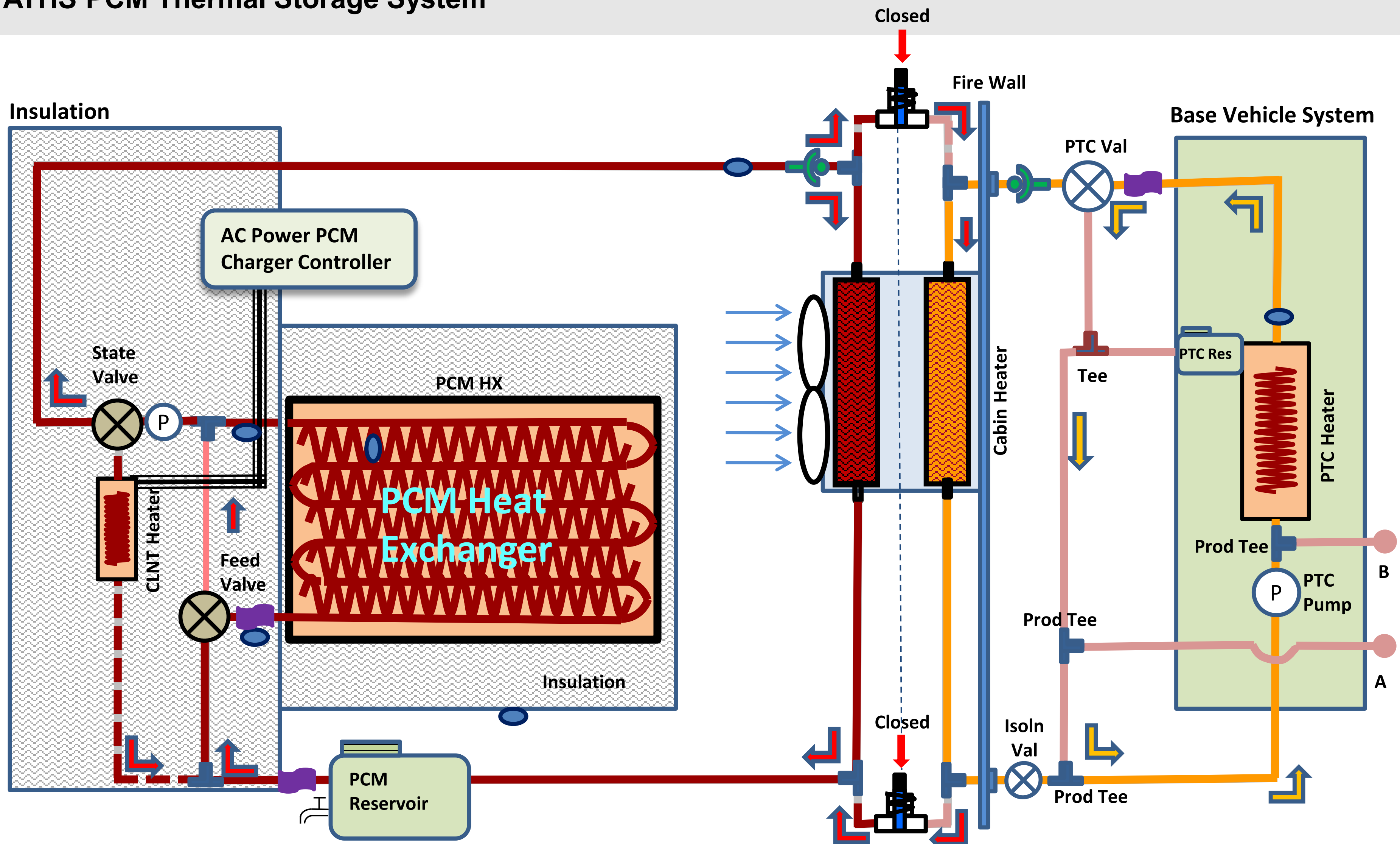


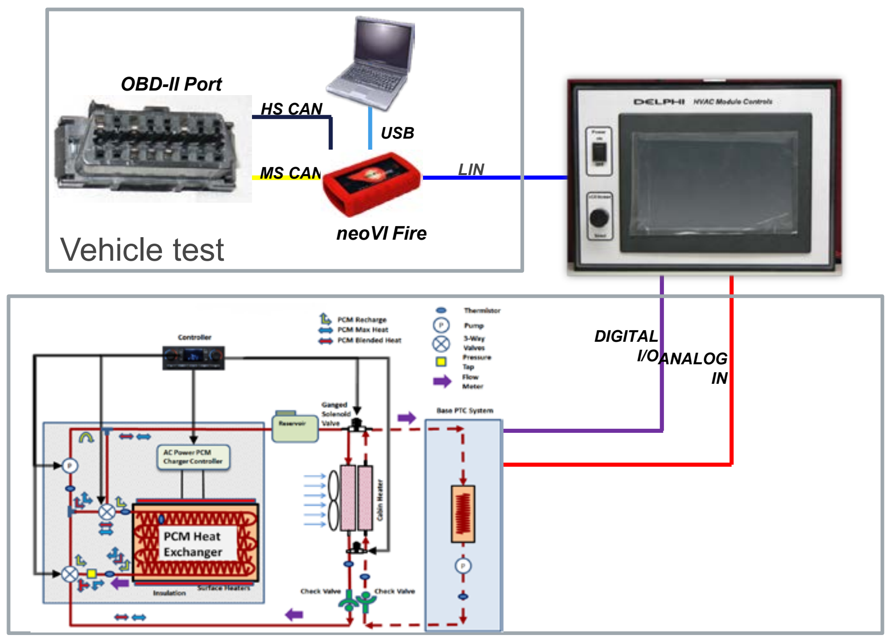
Controller and Control System Development

Bench and Car Controller Complete

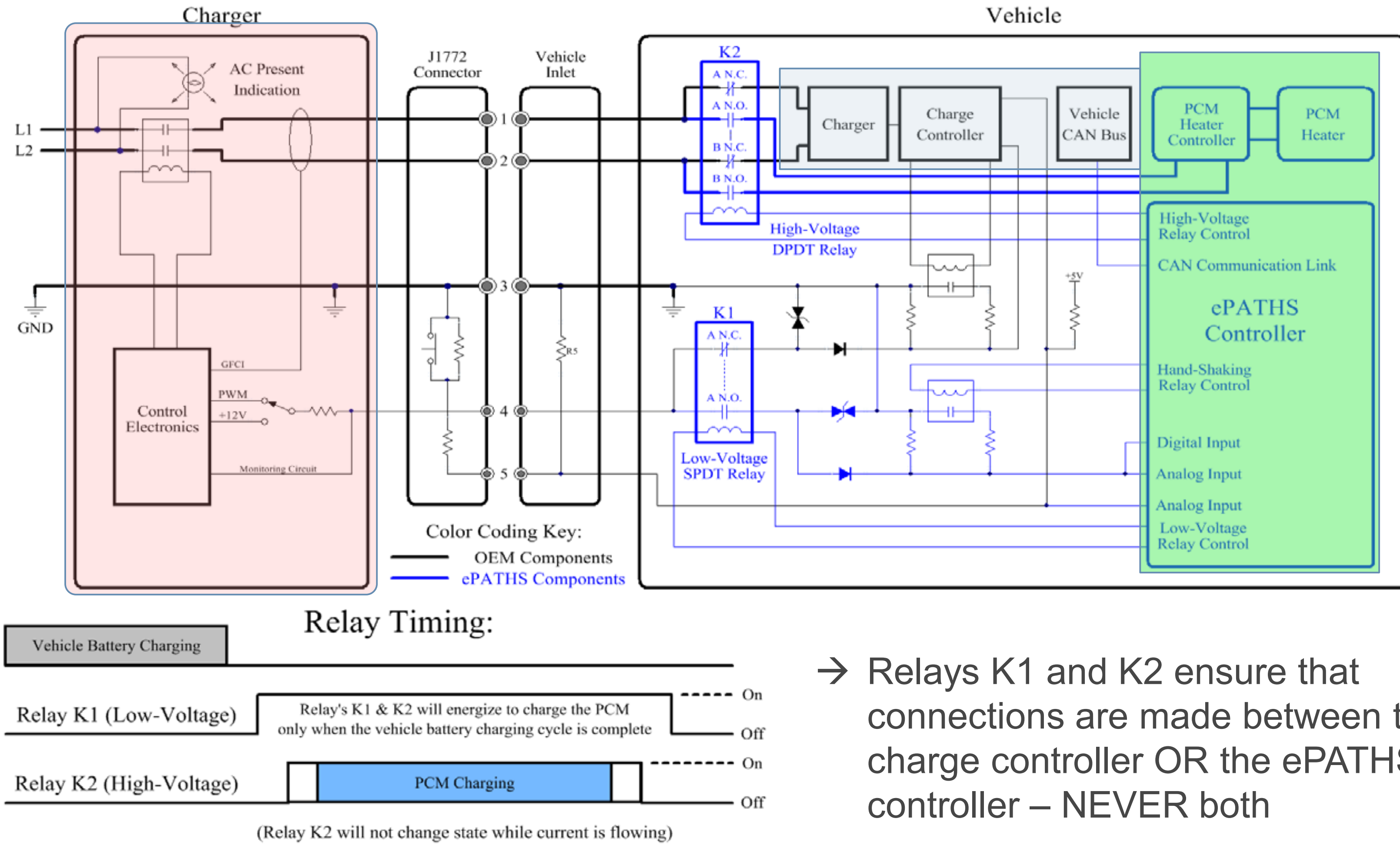
- 4 operating modes plus manual mode
- Touchscreen operation
- Displays key temperatures, valve and pump states
- Displays SOC of the PCM storage

Vehicle Control System Design

- neoVI Fire scripted to bridge ePATHS controller and vehicle bus
- ePATHS Controller
  - ✓ Monitors vehicle operation via bus
  - ✓ Supervises ePATHS system operation
  - ✓ Intelligent charging and discharge



Vehicle Charging System



→ Relays K1 and K2 ensure that connections are made between the car charge controller OR the ePATHS controller – NEVER both

Technical Accomplishments and Progress

Phase Change Material Development

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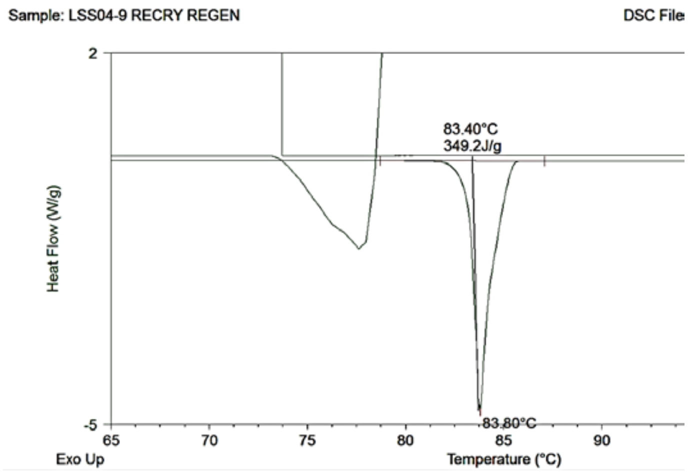
Objectives

- Development of PCMs that undergo phase change near 85 °C (vs. 90–100 °C)
- PCM with high latent heat (350 J/g)
- PCM thermally stable and able to withstand multiple (>1000) heating and cooling cycles.



Accomplishments

- 2 PCM materials have been developed, DPT68 and DPT83
- DPT68 synthesis and purification
  - Achieved pilot scale production for DPT68
  - Two 23 Kg batches were delivered to MAHLE in 2015
  - The material melts between 68-70 °C and produced a ≥340 J/g latent heat.
  - The material was used to fill two full sized heat exchangers.
- DPT 83 synthesis and purification
  - The production of DPT 83 is more challenging than DPT 68.
  - Numerous reaction variables had to be evaluated and optimized before large scale synthesis could begin.
  - Post reaction, several challenges such as polymerization of DPT 83 and metal catalyst removal were overcome.
  - Several distillation methods were evaluated to remove impurities. Current method of using an Oldershaw distillation column has greatly improved the purification process.
  - Distillation followed by recrystallization produces material with the desired specifications (≥340 J/g).
  - The current focus is the production of 5 Kg and 23 Kg batches for shipment of MAHLE.

Technical Accomplishments and Progress

Compatibility and Commercialization Studies

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Compatibility Study

Scope is evaluate compatibility between DPT68 and Aluminum Heat Exchanger

- DPT68 surrogate PCM for DPT83
- Same functional groups as DPT83

Systematic Evaluation

- Aluminum alloy (Al3003) coupons
- Coupons with Glycol based Noclok flux coating
- Coupons with dry Noclok flux coating
- Dry flux (powder) solubility

Results

- Al 3003 coupons exhibiting negligible corrosion rate
- Coupon Mass Loss Comparison:
  - *Al3003 < Dry Flux < Glycol Flux*
- Dry Flux powder has limited solubility in DPT68

Commercialization Study

Outside Contract Manufacturing

- A total of 28 vendors were contacted for the production of 1 million kilograms of DPT83.
- No individual vendor was capable of synthesizing DPT83; however, through a combination of different vendors, DPT83 could be synthesized on that scale.
- The costs associated would make the product not economically viable.

Designated Plant Construction

- The construction of a plant was also considered for the sole production of DPT83.
- Capital and Operating expenses were determined based on computer simulations.
- *This plant could generate the 1 million kilograms per year at price that would make the technology economically viable.*

Technical Accomplishments and Progress

Ford Focus BEV Packaging Study

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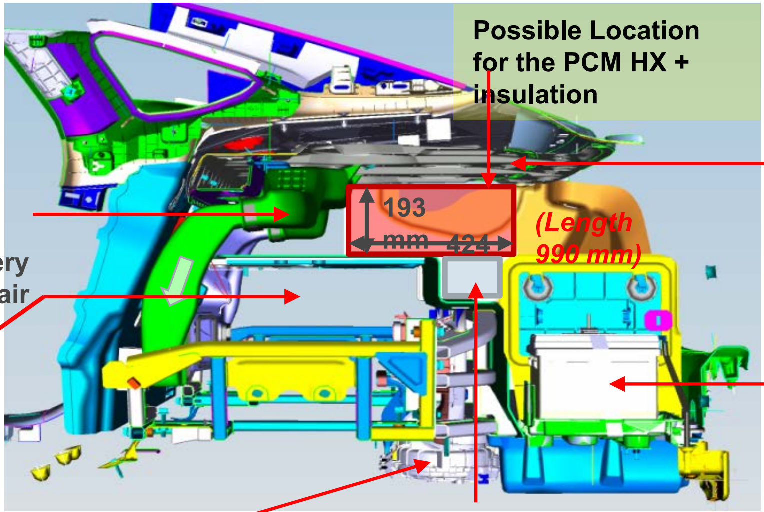
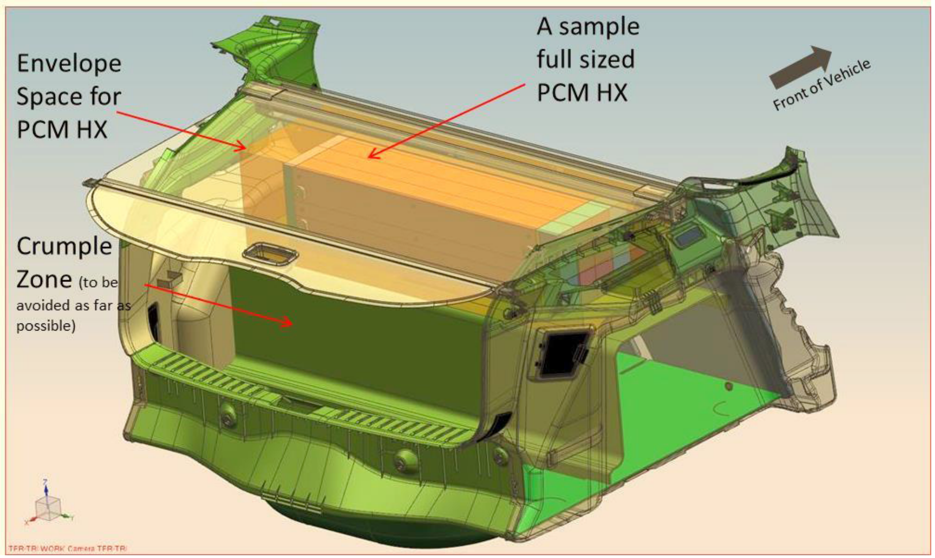
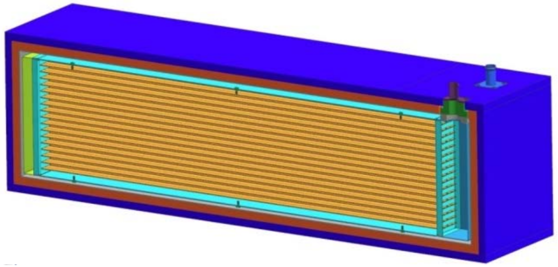
- Packaging studies have been performed for Ford Focus BEV and Ford Fusion Energi PHEV
- PCM HX sizing determined based on Ford Focus BEV packaging study.



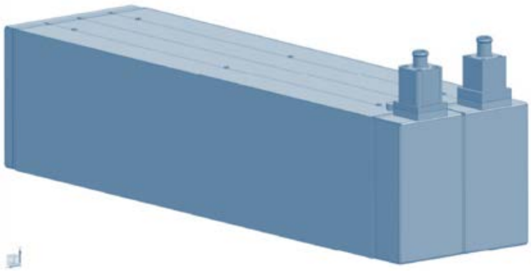


PCM Heat Exchanger Development

Four generations of PCM HX developed, with GEN IV in process



- GEN I design supported basic heat transfer and insulation development. Two quarter-size PCM HXs were fabricated with insulation



- GEN II design is a full sized PCM HX built for bench test
  - ✓ Dimensions: 826mmx191mmx221mm
  - ✓ Volume and Mass: 35 liters, 33 kg (20kg PCM + 13 kg Al)
  - ✓ Bench tested: Meeting thermal performance and energy storage targets
  - ✓ Challenges: Pressure handling, complicated manufacturing process

- GEN III HX Design
  - ✓ Low aspect ratio design for better insulation packaging
- GEN IV HX Design
  - ✓ Pressure handling capability to be enhanced
  - ✓ One step brazing, optimized for commercialization
  - ✓ Design being finalized for final vehicle demo

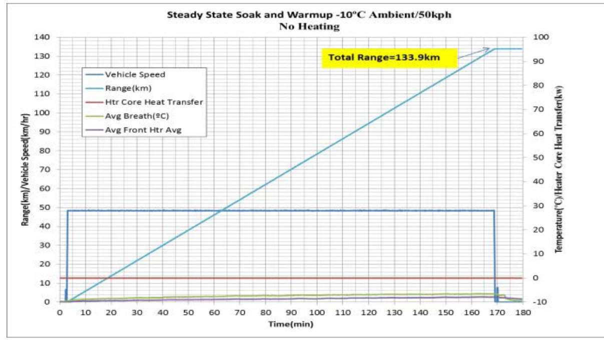
Climatic Tunnel Ford Focus Electric Baseline Testing

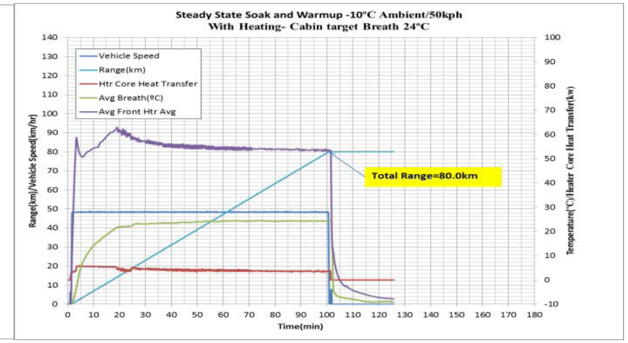
Objective

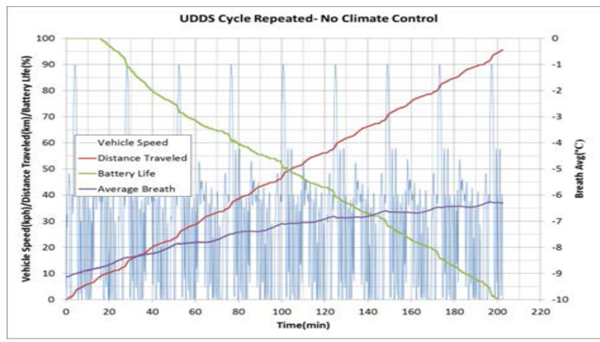
- Establish baseline range and heating performance at -10°C
- Measure the impact of production PTC cabin heating system on base range
- Range: Operating from full battery charge until 0 mile indicated range

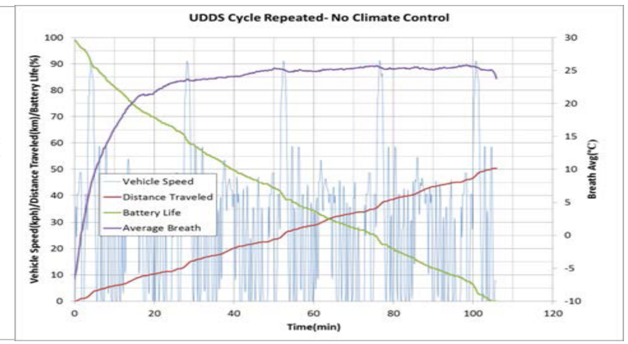
Test Summary

- -10°C Cold Soak to steady state heating – fingerprint vehicle operation
- 50 kph constant speed driving till full battery discharge
- Repeated UDDS cycles driving till full battery discharge
- All tests repeated for HVAC ON and OFF for range comparison









Test	No Heating Range(km)	Heating Range(km)	% Decrease in Range
Constant 50kph	134	80	40%
UDDS Cycle	95.5	50.4	47%

Technical Accomplishments and Progress

PCM Heating System Bench Build and Testing

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Bench test objectives

- Demonstrate control system functionality
- Perform PCM HX charging, discharging operations
- Evaluate charging/discharge rate for heating applications
- Evaluate heat storage capacity
- Evaluate thermal insulation effectiveness
- Evaluate vehicle range impact

Approach

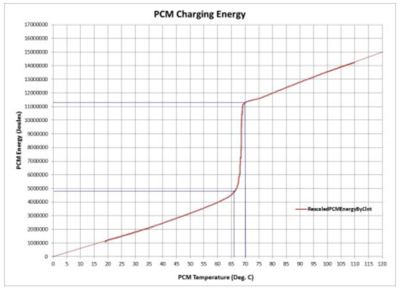
- Initial build, debugging and testing at MAHLE, Lockport, NY
- Validation testing at ORNL

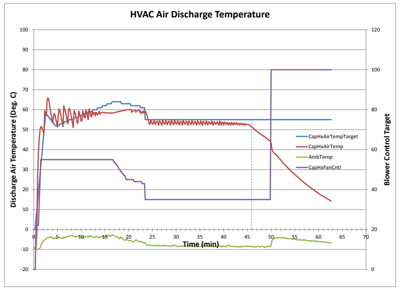
PCM HX charging

- Coolant heater used for charging
- Charge to 110 Deg. C
- At 110 Deg. C, 14.2 MJ energy storage, with 0 Deg. C ref.
- Latent heat ~= 344 j/g

PCM HX discharging

- Discharge air temperature requirement under specified blower duty cycle is met with PCM charged to 110 Deg. C
- Maintained required air temperature for 46 minutes
- Energy recovery tested under 35% and 100% blower duty cycle





Cases	Units	Energy_120	Energy_60	Energy_25	Heat_120~60	Heat_25~60	Total
Projection with h=340 j/g	MJ	15.8	6.4	3.2	9.5	3.2	12.7
	kWh	4.40	1.77	0.88	**2.64**	**0.88**	**3.52**
Surface Heater	MJ	15.0	6.9	2.8	8.1	4.1	12.2
	kWh	4.17	1.93	0.78	**2.24**	**1.15**	**3.39**

Analysis Indicates

- Projected Focus BEV base range extension:10.3~14.1 miles, percentage range extension: 21~28%
- Projected Focus BEV total range extension with energy recovery: 15.6~17.3 miles, percentage range extension:31~34%

Technical Accomplishments and Progress

Oak Ridge National Lab Confirmation Testing

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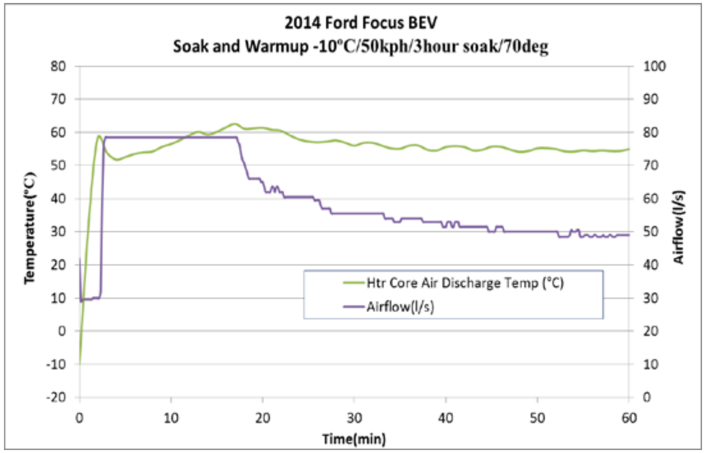
Work completed at ORNL, November 2015-February 2016
- Evaluation of ePATHS charging, discharge, and insulation system perform.
- Validation that performance targets were satisfied for the prototype system

Evaluations simulated operation in an EV
- Heating profile, thermal load matched to measured conditions in a Ford Focus BEV
- Environmental chamber maintained controlled winter-like ambient conditions, identical temperature

Cumulative energy stored and discharged from the ePATHS exceeded design targets
- 13 MJ usable energy storage for discharge to 60°C (target: 12.6 MJ)
- Stored energy was enough to provide over 50 minutes of cabin heating at an ambient condition of -10°C.

Cold soak thermal losses also lower than expected
- 4.1-8.0% loss during 8 hours, depending on temperature (target: <10%)

Challenges–charging and discharge control improvement
- Coolant boiling regularly occurred during charging, need better control of applied power
- Outlet vent air temperature exhibited oscillations, modified bypass flow control being addressed



Collaboration and Coordination

Working Together!

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MAHLE Is Lead Organization

- Significant automotive experience. HVAC system, compressor, heat exchanger development expertise and global manufacturing footprints
- Responsible for system and components design, development and vehicle integration

Strong Sub-Recipient Teams

- Ford – OEM who produces GCEV
- ORNL – Modeling and analysis in transportation technologies
- Entropy – Leading PCM technology and material supplier

Weekly Project Execution Meetings

- Focus on task execution and timing
- Resolve technical and resource issues
- Communication

Face to Face Technical Meetings

- Regular site visits and as-needed technical meetings

Future Work

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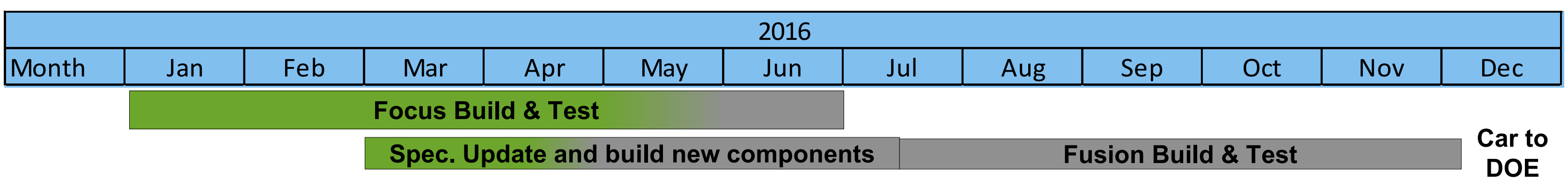
FY16: Technology Integration and Validation

- Finalize system and components specifications
- Finalize components and system design for vehicle integration
- Fabricate PCM Heat Exchanger for thermal storage
- Integration ePATHS system into Ford Focus BEV
- Evaluate Focus BEV range impact of ePATHS system
- Integration of ePATHS system into Ford Fusion PHEV
- Evaluate Fusion PHEV range impact of ePATHS system

- Work plan:



Response to Previous Year Reviewers' Comments

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Comments from 2015 AMR	Response
"… The reviewer still has interest in off-grid soak time versus effectiveness for this type of technology, and how this will affect thermal battery management. The reviewer asked if there will be a durability side effect.	The design target for heat loss over 8 hours of off-grid parking lot soak is 10% (or a half life of 53 hours). A fully charged battery should still be able to provide heating for a single trip of the commute after 53 hours. The thermal battery management strategy will likely be "Charge whenever possible". Durability is impacted by material compatibility, thermal cycling, and pressure cycling. The latter two has led to a PCM HX redesign.
" … It would be useful to show sizing and heating demographics needed and where the system will or will not work (or what size systems would be needed for various temperatures/humidity levels). The reviewer added that extended soak requirements might be needed to accommodate periods where a vehicle is not parked in garage (and plugged in) and how long thermal storage could last. In these cases, a comparison of grid energy required to heat phase change material (PCM) versus battery energy required to heat and/or maintain PCM would be useful, especially as it compares to the baseline battery heating system.."	The thermal storage is designed for the nominal ambient of -10°C to provide heating for a round trip commute to work. It assumes a preconditioned cabin from home, an 8 hour period of off-grid soak time (heat loss), and a transient warm-up during the return trip. For the US, designing for -10°C would satisfy 90% of US geographical areas for round trip commute with an 8 hour parking period. For geographical areas with lower than -10°C winter, the return trip likely will not be fully heated and electric heating will be required. This will translate into reduced range. Finally, the current system is not designed to be maintained by the electric traction battery. Referencing answer to first question, the operating strategy for the thermal battery would be top-off charging whenever possible.

Summary

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- **Relevance:** Thermal storage helps to address the critical concern of “Range Anxiety” for electric vehicles, thereby furthering VTO’s objective of range extension
- **Approach:** A diversified team of vehicle OEM, Tier-1 Thermal Supplier, transportation National Laboratory, leading PCM supplier employing proven product development process to achieve an integrated BEV thermal storage system.
- **Accomplishments:** Prototype thermal storage system has been successfully integrated on the bench, achieving thermal charging and discharging, meeting the thermal storage capacity target.
- **Collaboration:** The project team has continued working closely through weekly meetings, even daily meetings when needed. Regular site visits allows face-to-face exchanges. Team members enjoyed close working relationship and mutual support.
- **Future Work:** FY16 project timeline allows for integration of ePATHS system into both a BEV and a PHEV for range impact evaluation and demonstration.